Normal-state properties of $YBa_2Cu_3O_y$ in high magnetic fields

Toulouse
80T pulsed field

Grenoble
35T static field

Sven Badoux LNCMI

séminaire Roscoff, 09 janvier 2013

LNCMI

C. Proust (T)

D. Vignolles (T)

B. Vignolle (T)

D. LeBœuf (T)

S. Lepault (T)

L. Malone (G)

M-H. Julien (G)

T. Wu (G)

UNIVERSITÉ DE SHERBROOKE

L. Taillefer

N. Doiron-Leyraud

University of BRISTOL

N. Hussey

A. Carrington

UBC

D. Bonn

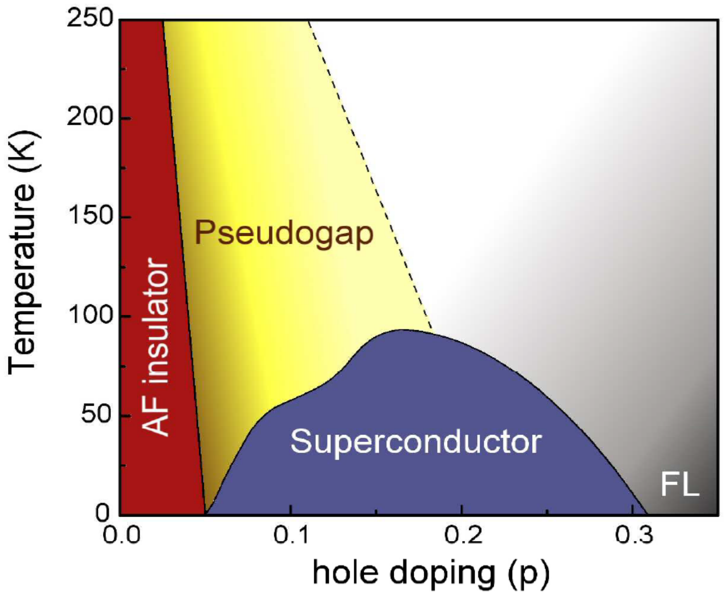
B. Ramshaw

J. Day

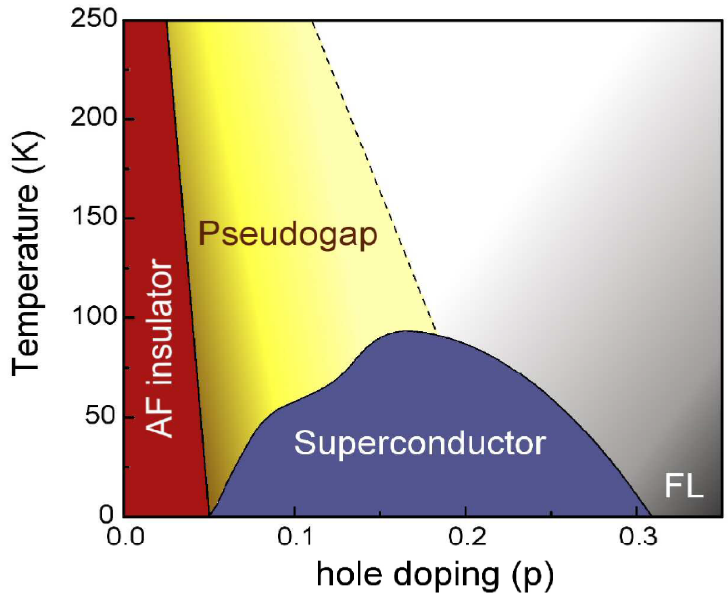
R. Liang

W. Hardy

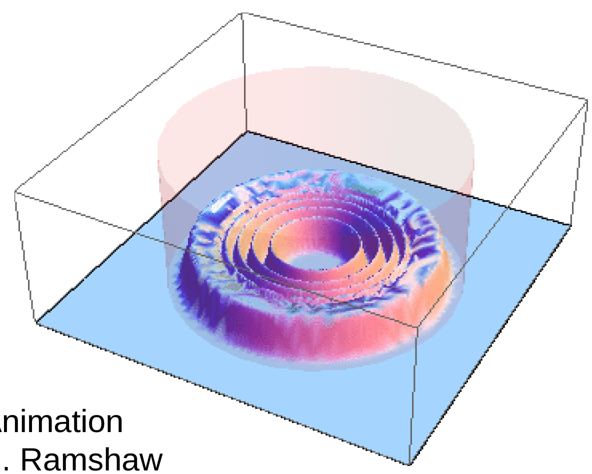
Phase diagram



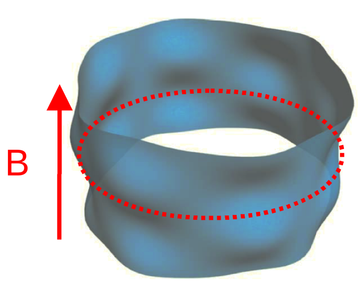
underdoped overdoped



underdoped overdoped



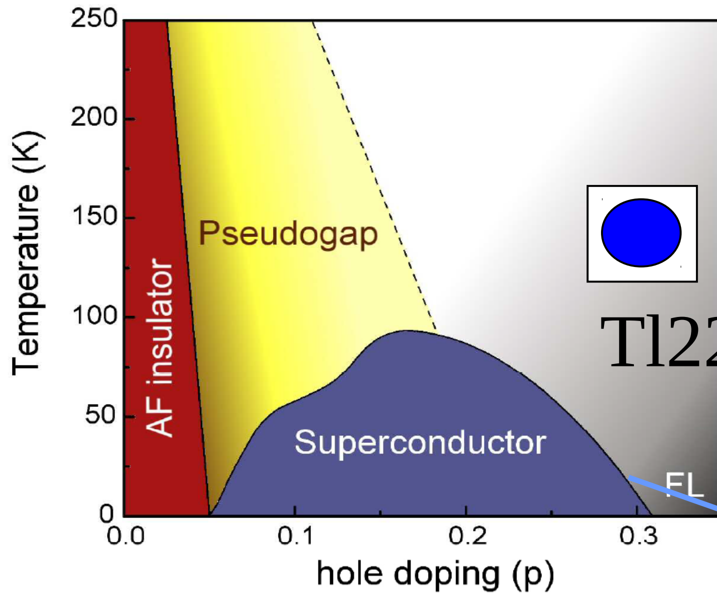
Animation
B. Ramshaw



Quantum oscillations
(SdH or dHvA)

1/B periodicity

$$F(T) = \frac{\varphi_0}{2\pi^2} A_k$$

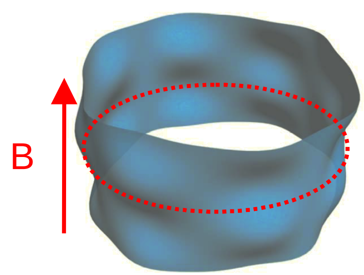


overdoped
$Tl_2Ba_2CuO_{6+\delta}$

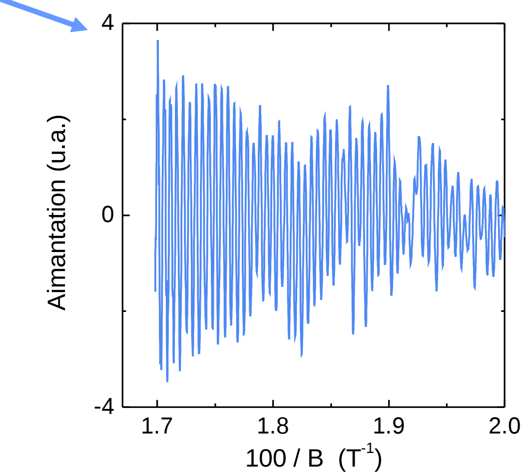
Frequency : F = (18100 ± 50) *T*

A_k = *65 %* *of 1st Brillouin zone*

underdoped overdoped



$$F = \frac{\varphi_0}{2\pi^2} A_k$$

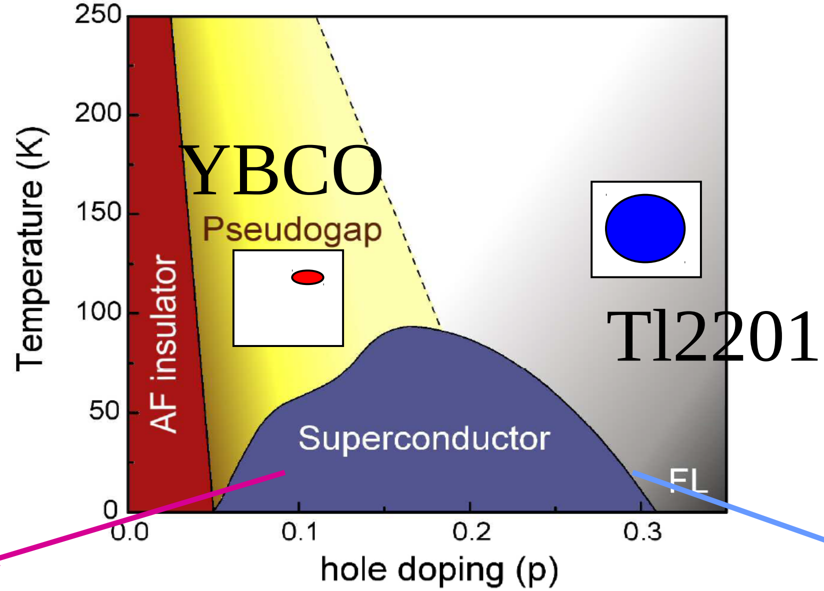


B. Vignolle et al, Nature'08

underdoped
$YBa_2Cu_3O_{6.5}$

Frequency : F = (530 ± 20) T

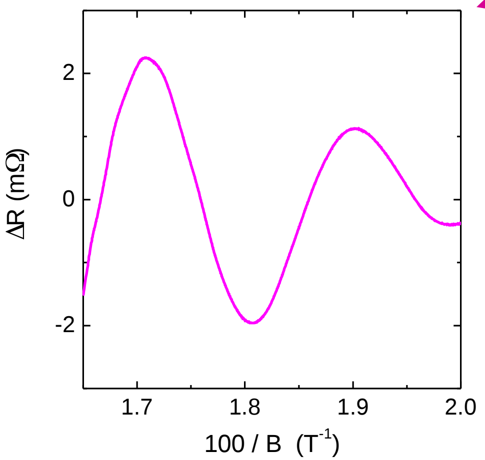
A_k = 1.9 % *of 1st Brillouin zone*



overdoped
$Tl_2Ba_2CuO_{6+\delta}$

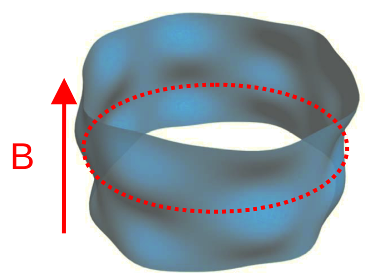
Frequency : F = (18100 ± 50) T

A_k = 65 % *of 1st Brillouin zone*

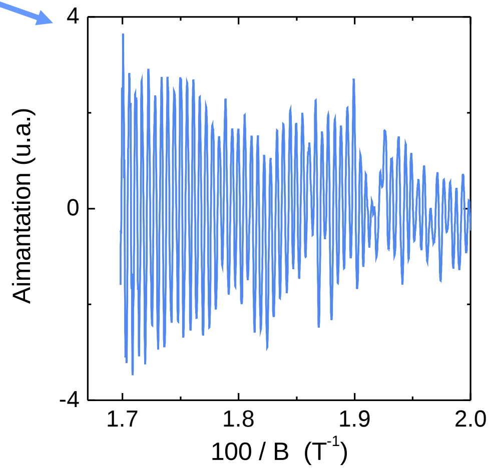


N. Doiron-Leyraud et al, Nature'07

underdoped ⟵ ⟶ overdoped



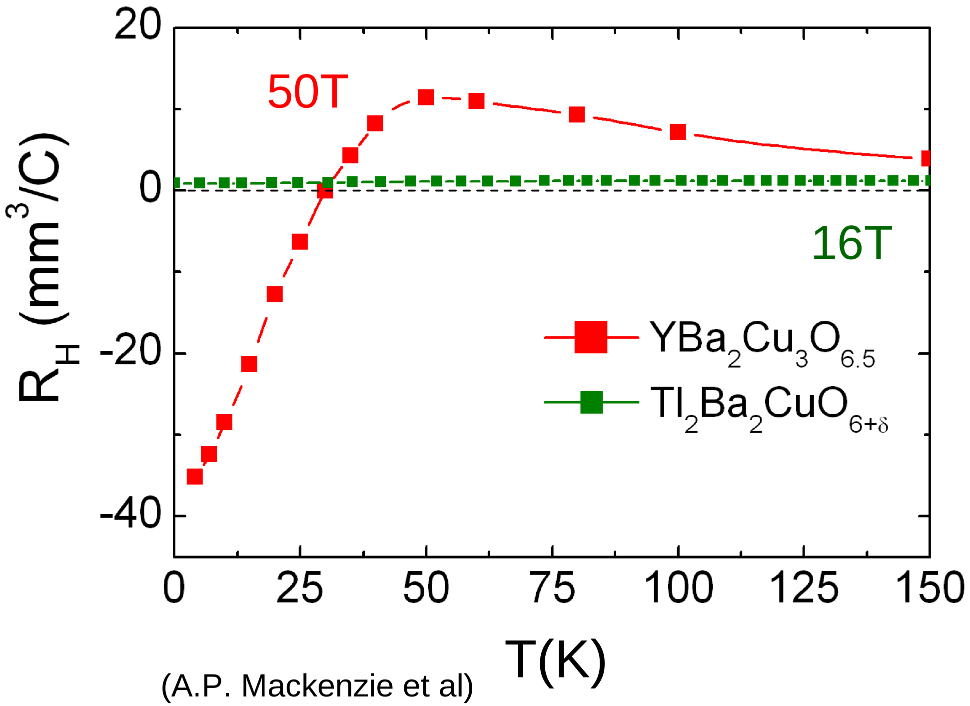
$$F = \frac{\varphi_0}{2\pi^2} A_k$$



B. Vignolle et al, Nature'08

Drastic change of the Fermi surface size

Hall coefficients in Cuprates



(A.P. Mackenzie et al)
(D. LeBoeuf et al)

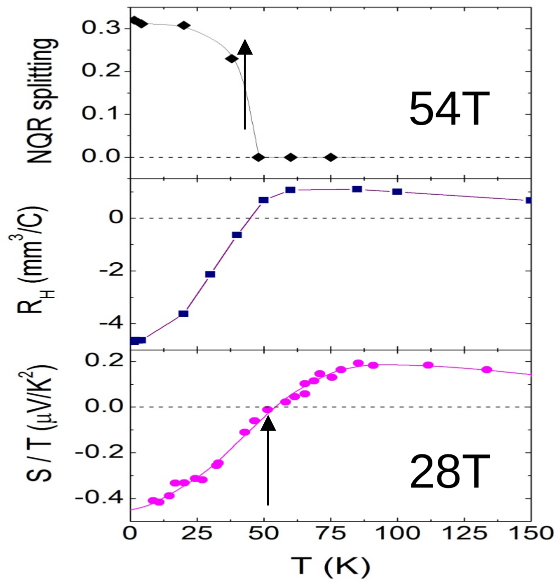
Overdoped cuprates:
-Hole pocket

Underdoped cuprates:
-Electron pocket at low T

Fermi surface reconstruction

What is the order responsible for the reconstruction?

$YBa_2Cu_3O_y$ p~0.11

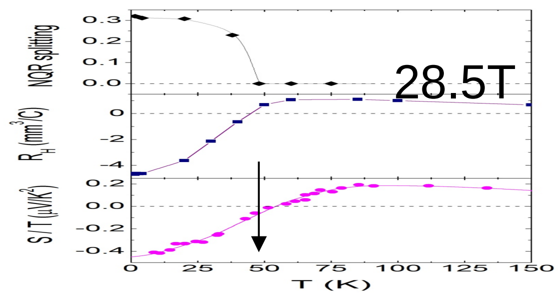


Hall effect

D. LeBoeuf et al, PRB’11

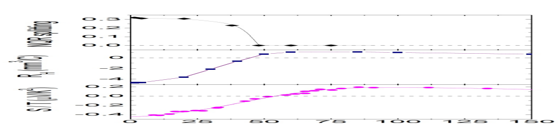
Thermopower

F. Laliberté et al, Nature Comm’11



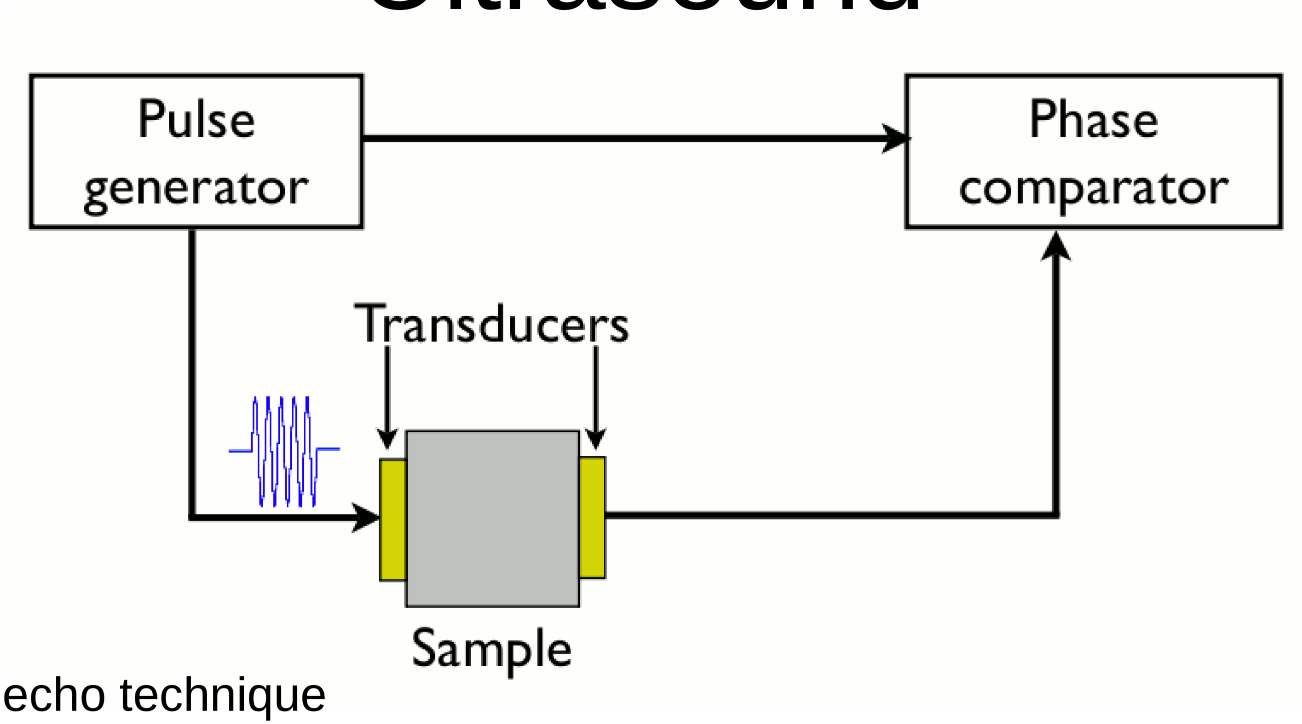
NMR

T. Wu et al, Nature’11



Charge order detected by NMR

Ultrasound



- Pulsed echo technique

- Sound velocity: thermodynamic quantity related to the elastic constants of a solid

- Sensitivity ~1ppm

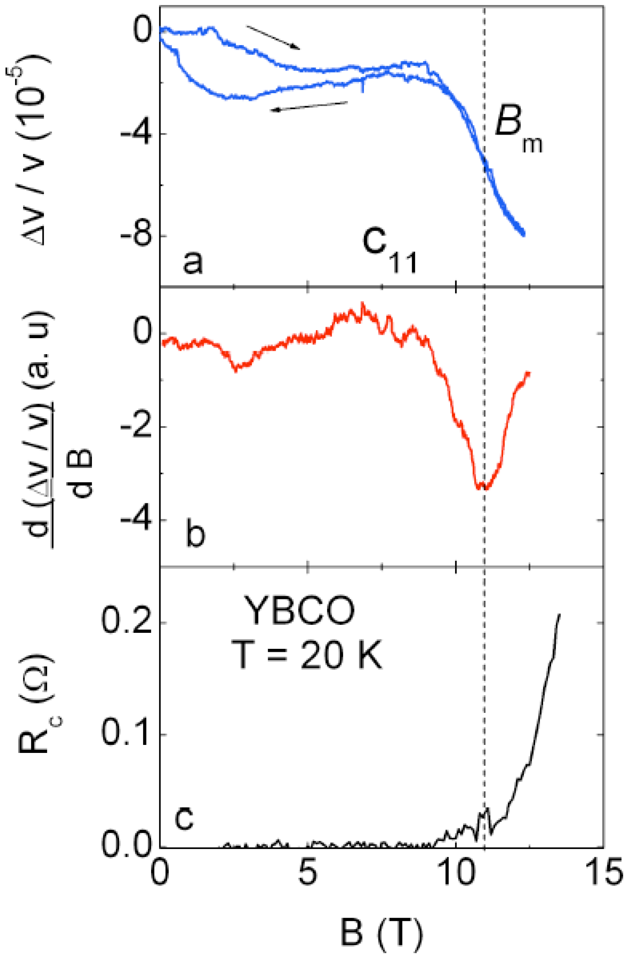
- No indication about the nature of the transition

$$v_s^2 = \frac{c_{ij}}{\rho} \quad ; \quad c_{ij} = \frac{\partial^2 F}{\partial \varepsilon_i \partial \varepsilon_j}$$

~km/s

Determination of B_m

(solid liquid vortex transition)

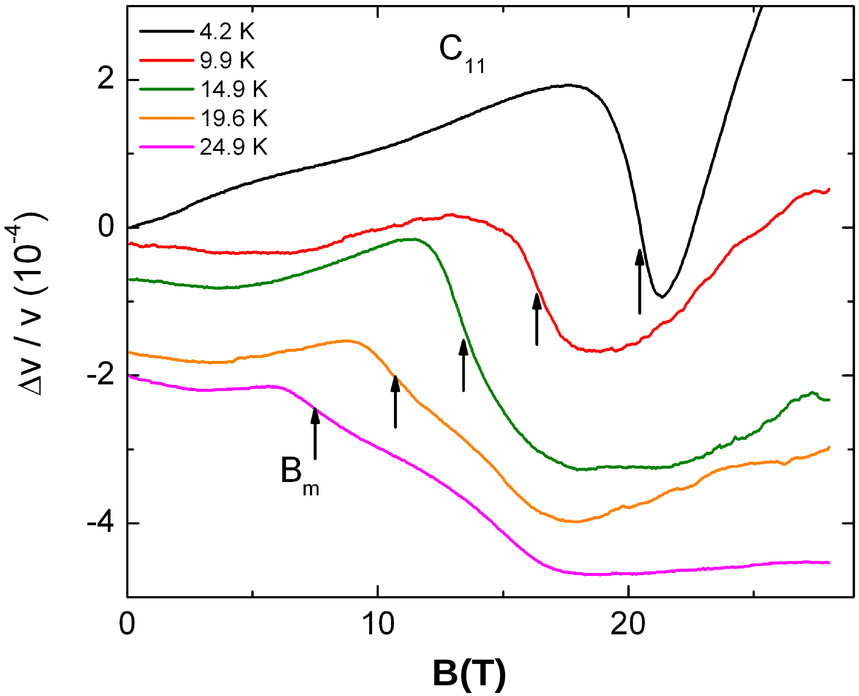


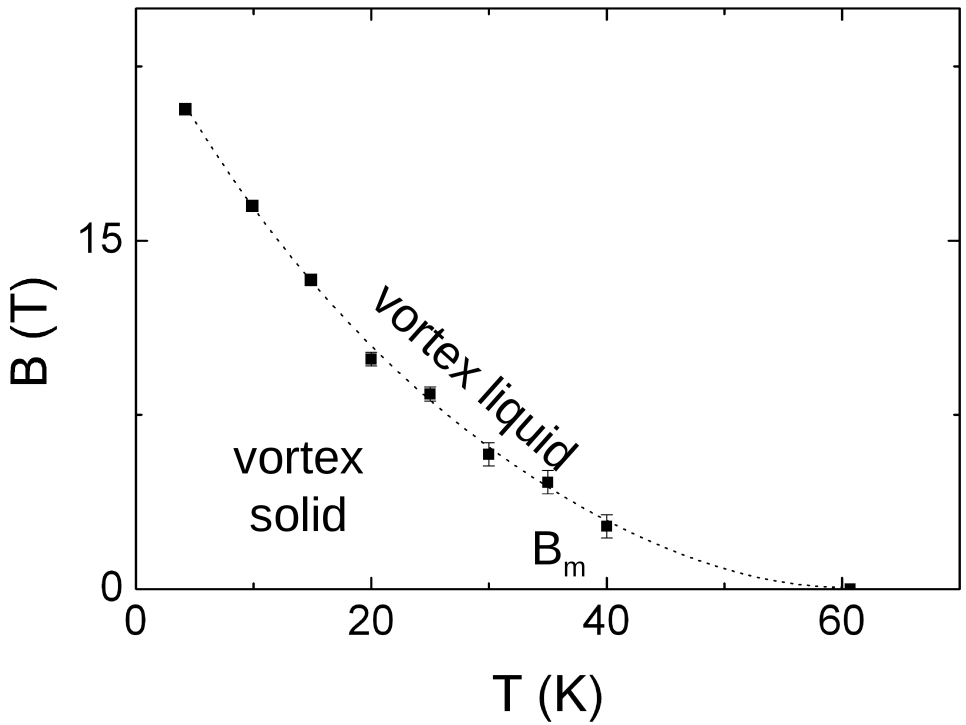
Sound velocity

Derivative

Magnetoresistance

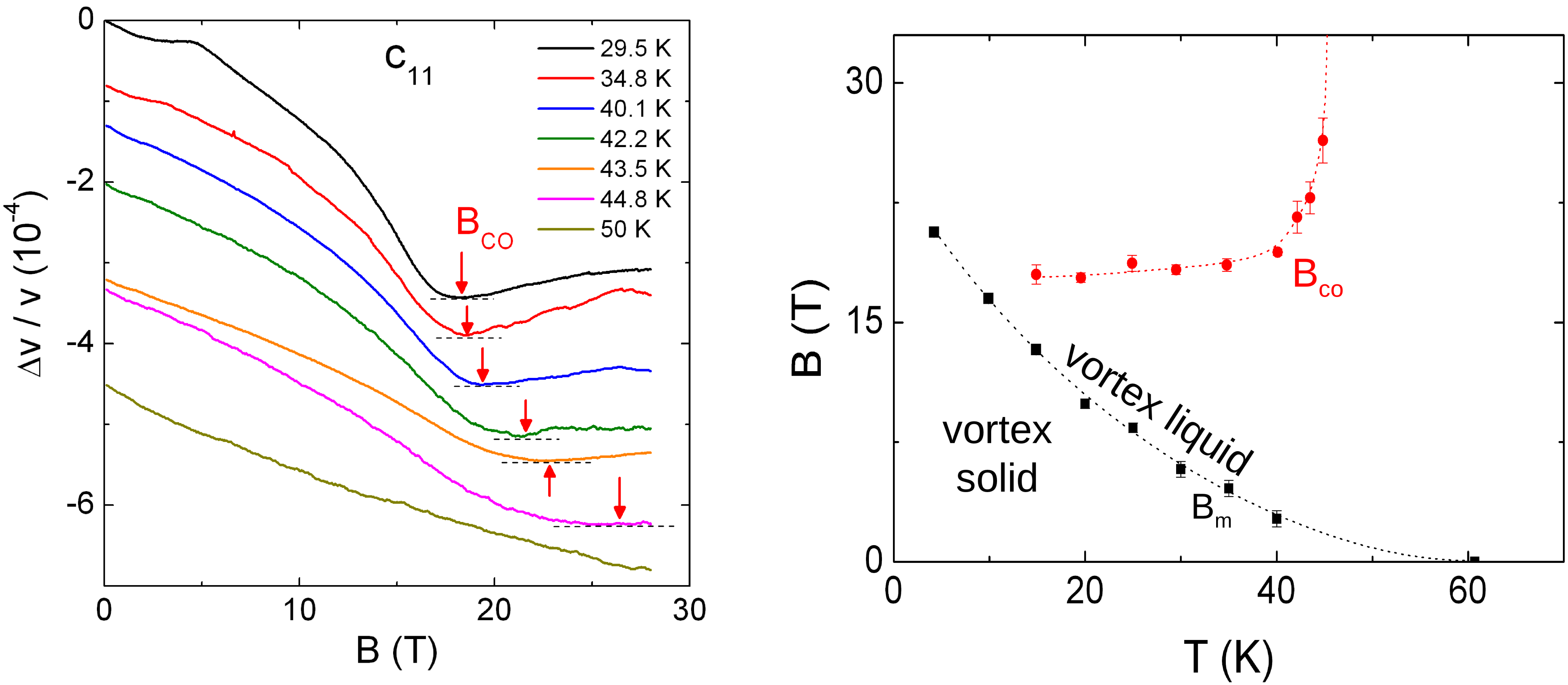
Determination of B_m
(solid liquid vortex transition)





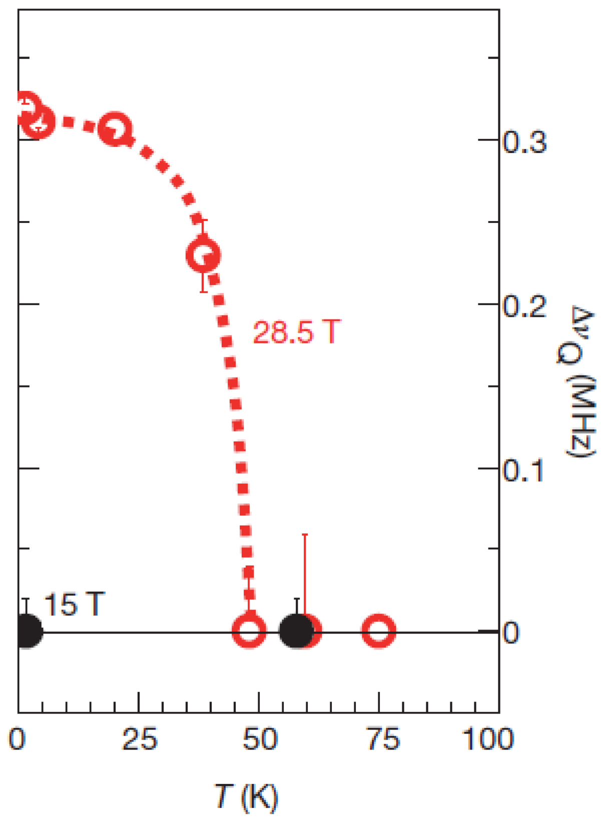
Transition is in good agreement with the expected phase diagram

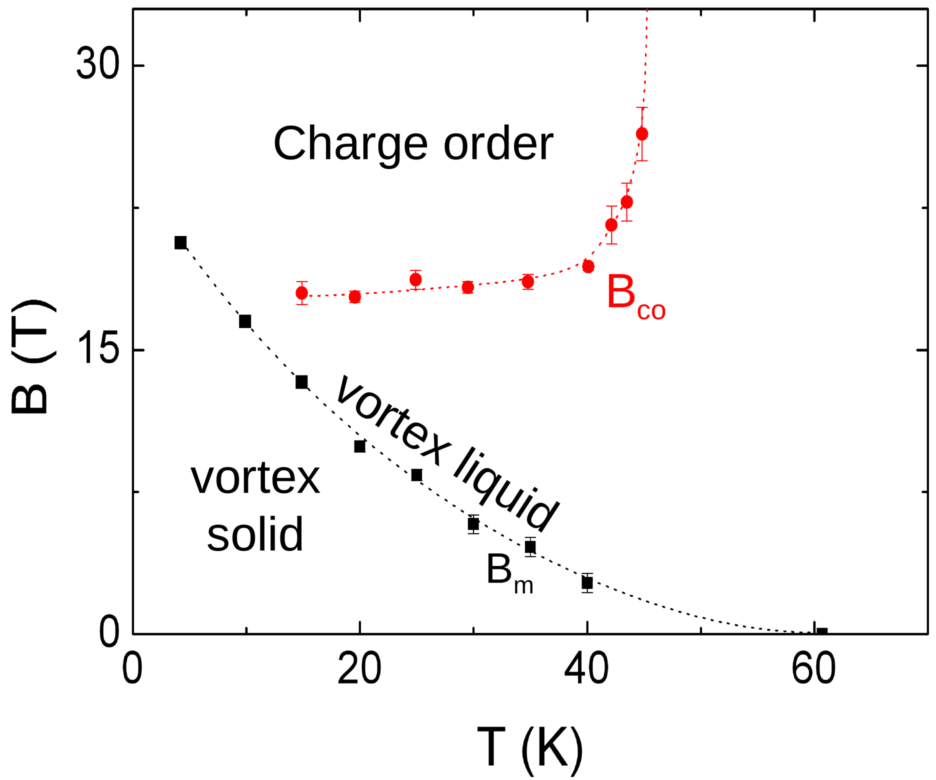
Tracking of the anomaly B_{co}



What is the nature of the transition responsible for this anomaly?

Tracking of the charge order transition B_{co}





First thermodynamic determination of the field induced competing charge order

Symmetry of charge order

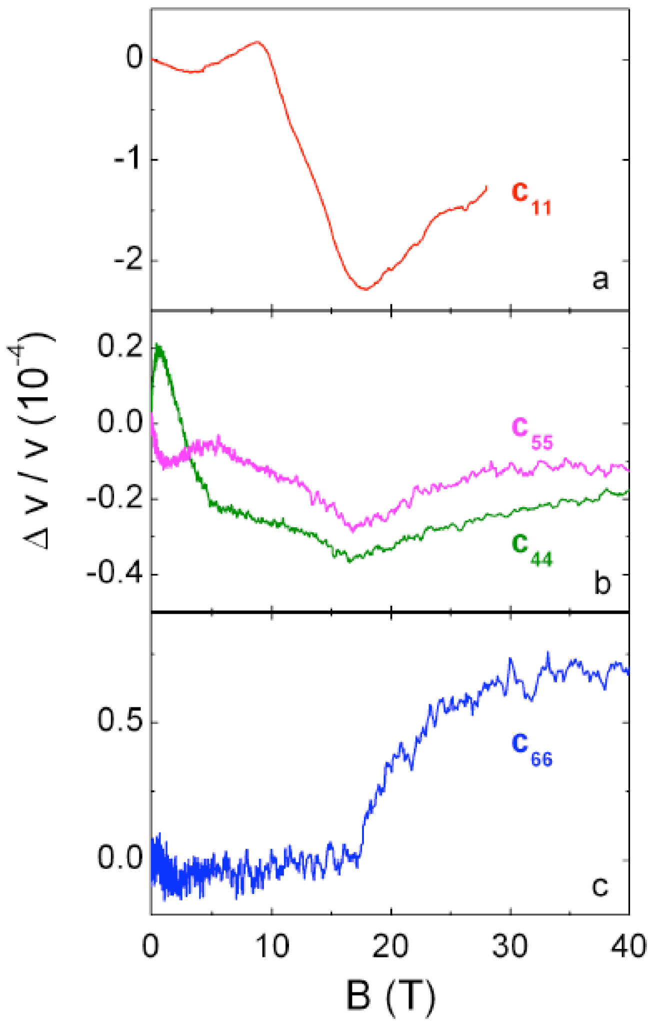
Mode	Propagation vector *q*	Polarisation vector *u*
c_{11}	[1,0,0]	[1,0,0]
c_{44}	[0,1,0]	[0,0,1]
c_{55}	[1,0,0]	[0,0,1]
c_{66}	[0,1,0]	[1,0,0]

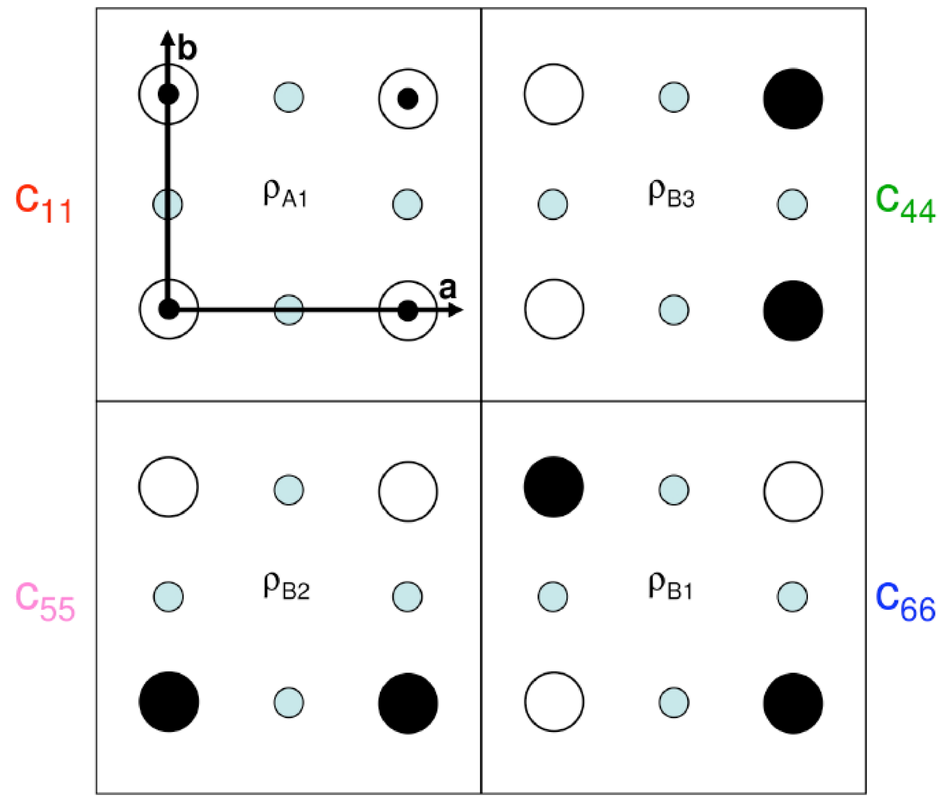
Order parameter-strain coupling:

$$F_c = g_{mn}\, Q^m\, \varepsilon^n$$

Such coupling is symmetry allowed only if ε^n and Q^m transform according to the same irreducible representation

Symmetry of charge order





Bi-axial charge order

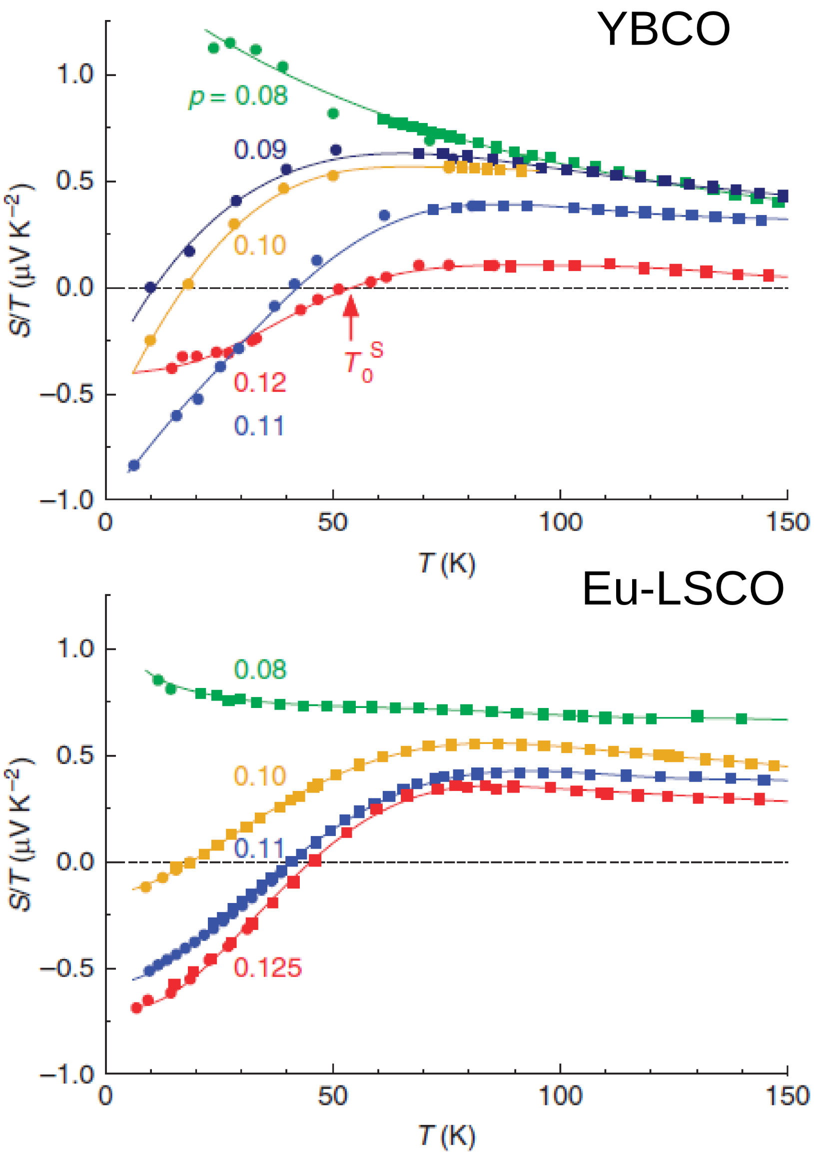
Conclusion

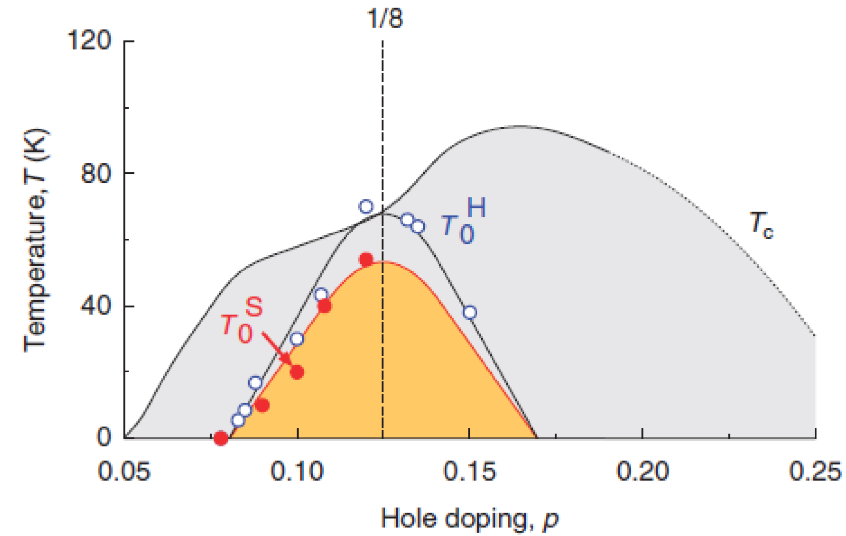
• Charge order in competition with superconductivity

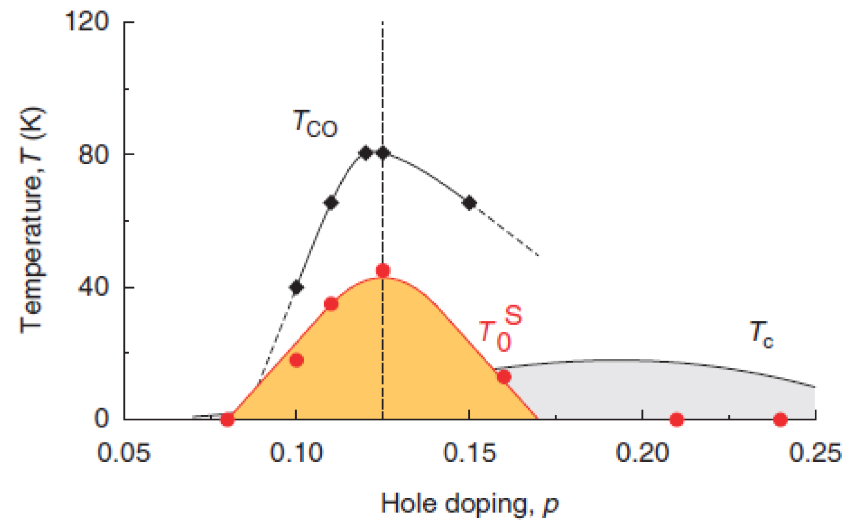
• Sound velocity is at the moment the only thermodynamic probe available to study in high field the charge order observed in underdoped cuprates

• Bi-axial charge order detected by sound velocity

Doping dependence of Seebeck coefficients in YBCO and Eu-LSCO

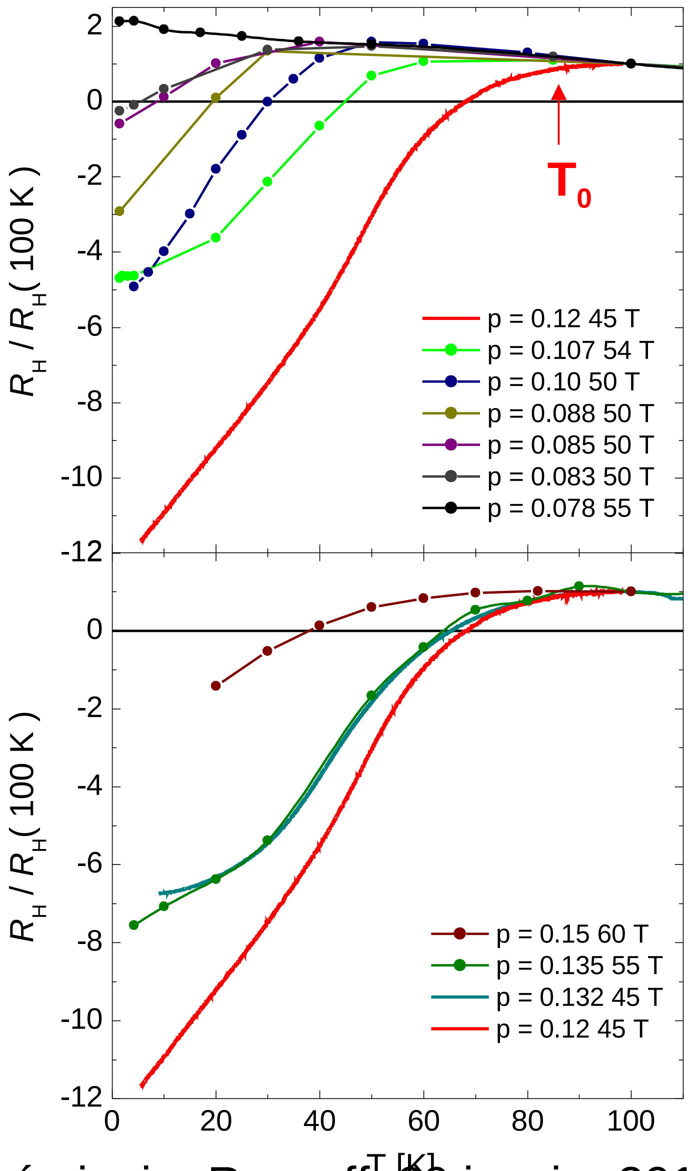


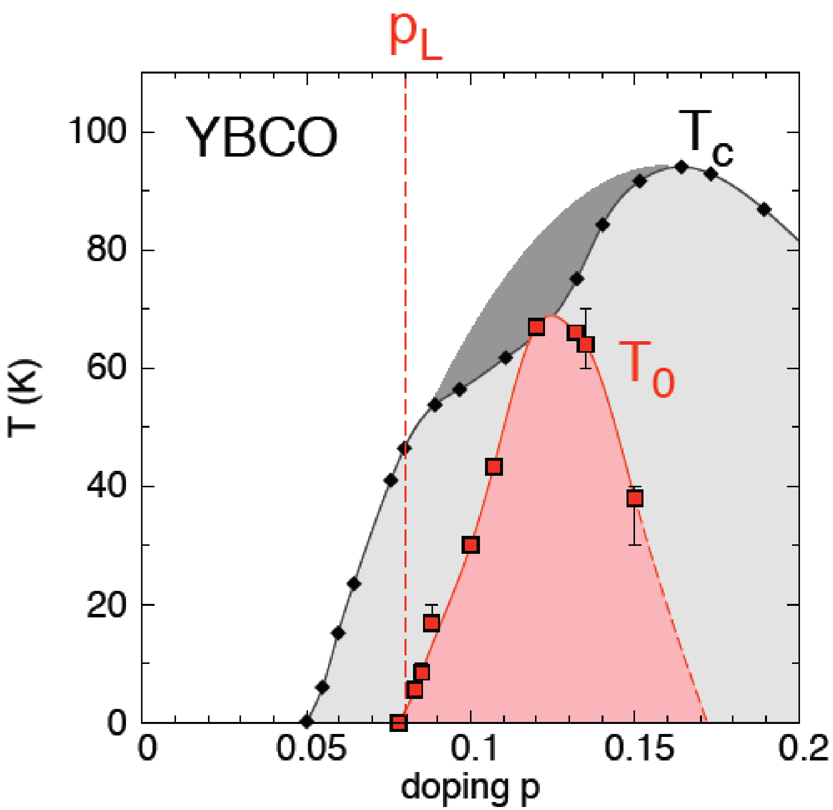




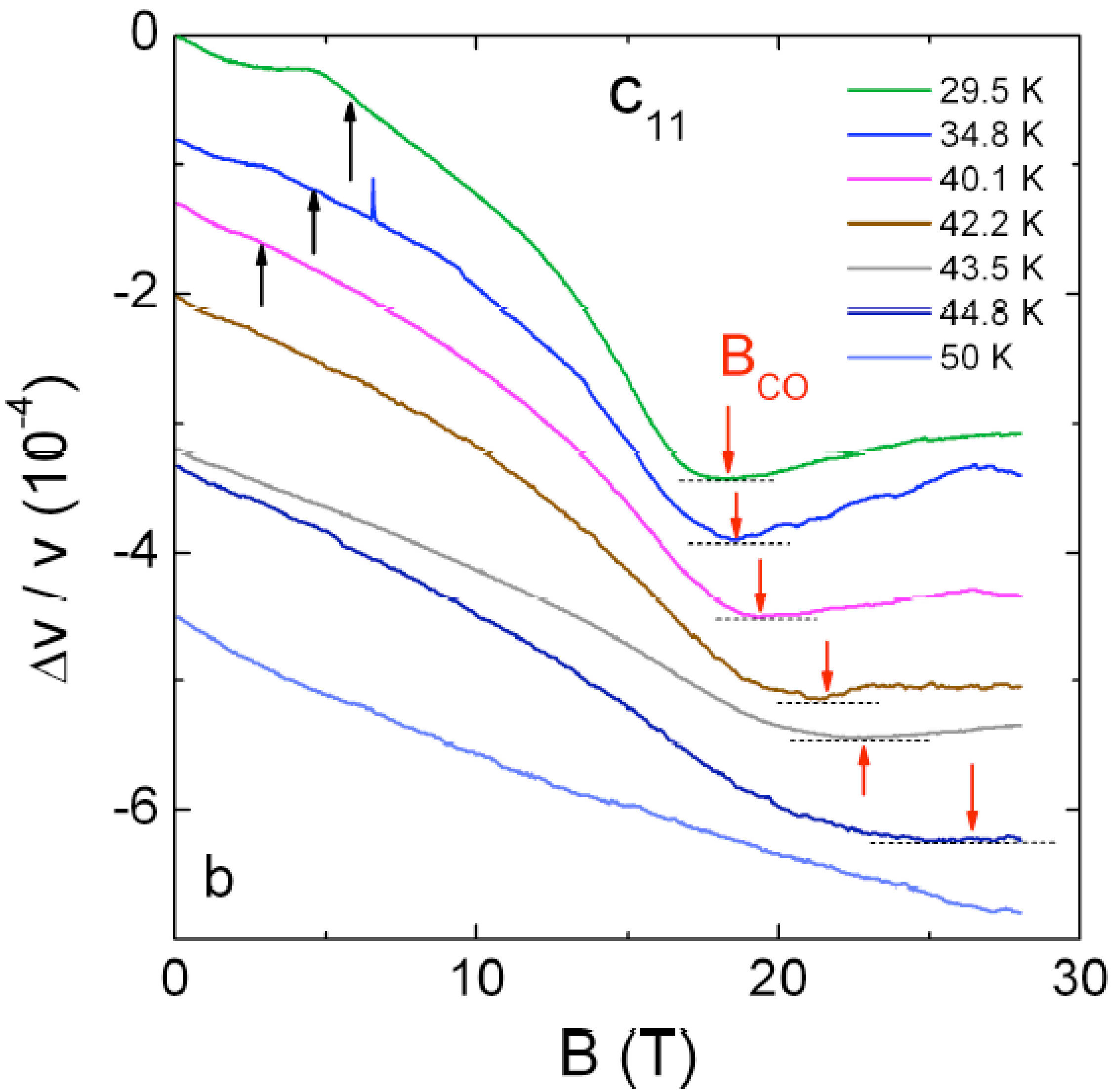
(F. Laliberté et al, Nature Comm.’11)

Doping dependence of Hall coefficients in YBCO

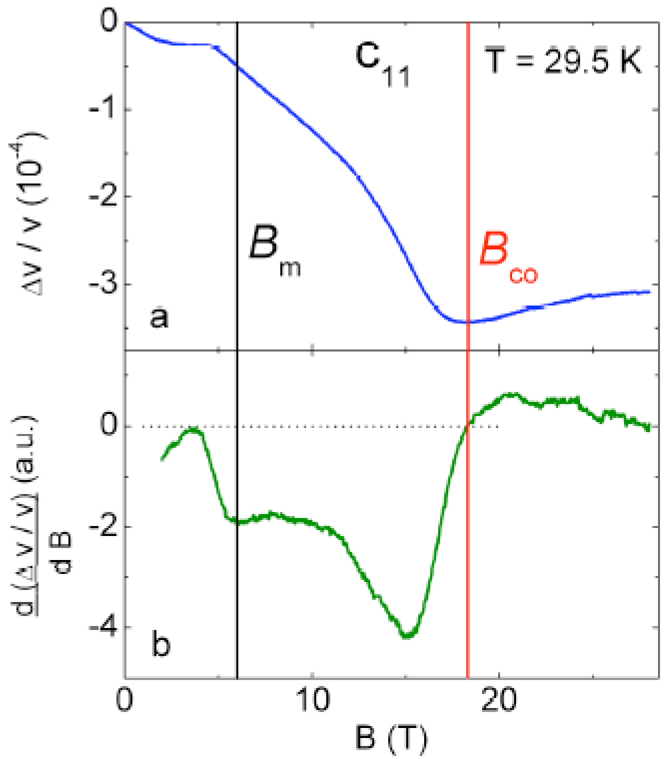




D. LeBoeuf et al, PRB’11



c11
29.5 K
34.8 K
40.1 K
42.2 K
43.5 K
44.8 K
50 K
B_CO
b
Δv / v (10^-4)
B (T)
0
-2
-4
-6
0
10
20
30

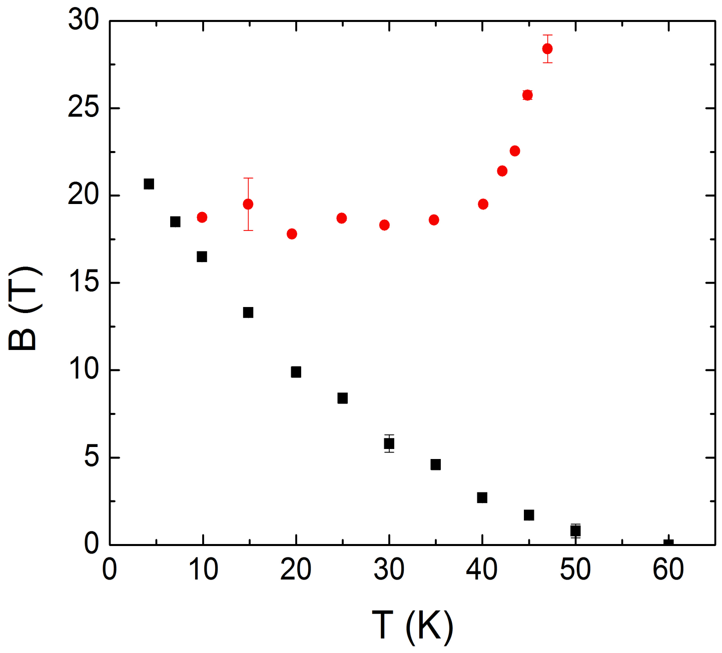


c11
T = 29.5 K
B_m
B_co
a
b
Δv / v (10^-4)
d(Δv / v) / dB (a.u.)
B (T)
0
10
20

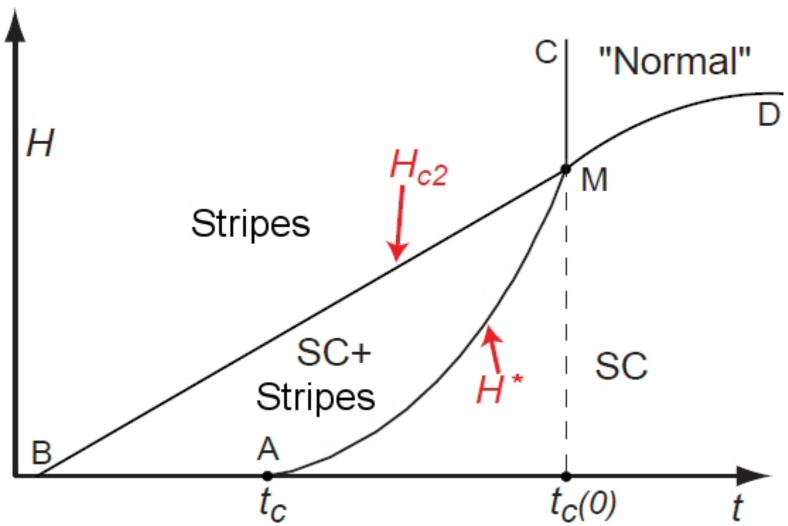
Irr. Rep.	E	C_2^z	C_2^y	C_2^x	Basis functions	Symmetric strains
A_{1g}	1	1	1	1	x^2 , y^2 , z^2	Volume strains : ε_1
B_{1g}	1	1	-1	-1	z, xy	ε_6
B_{2g}	1	-1	1	-1	y, xz	ε_5
B_{3g}	1	-1	-1	1	x, yz	ε_4

Field stabilized charge-stripe order in competition with superconductivity

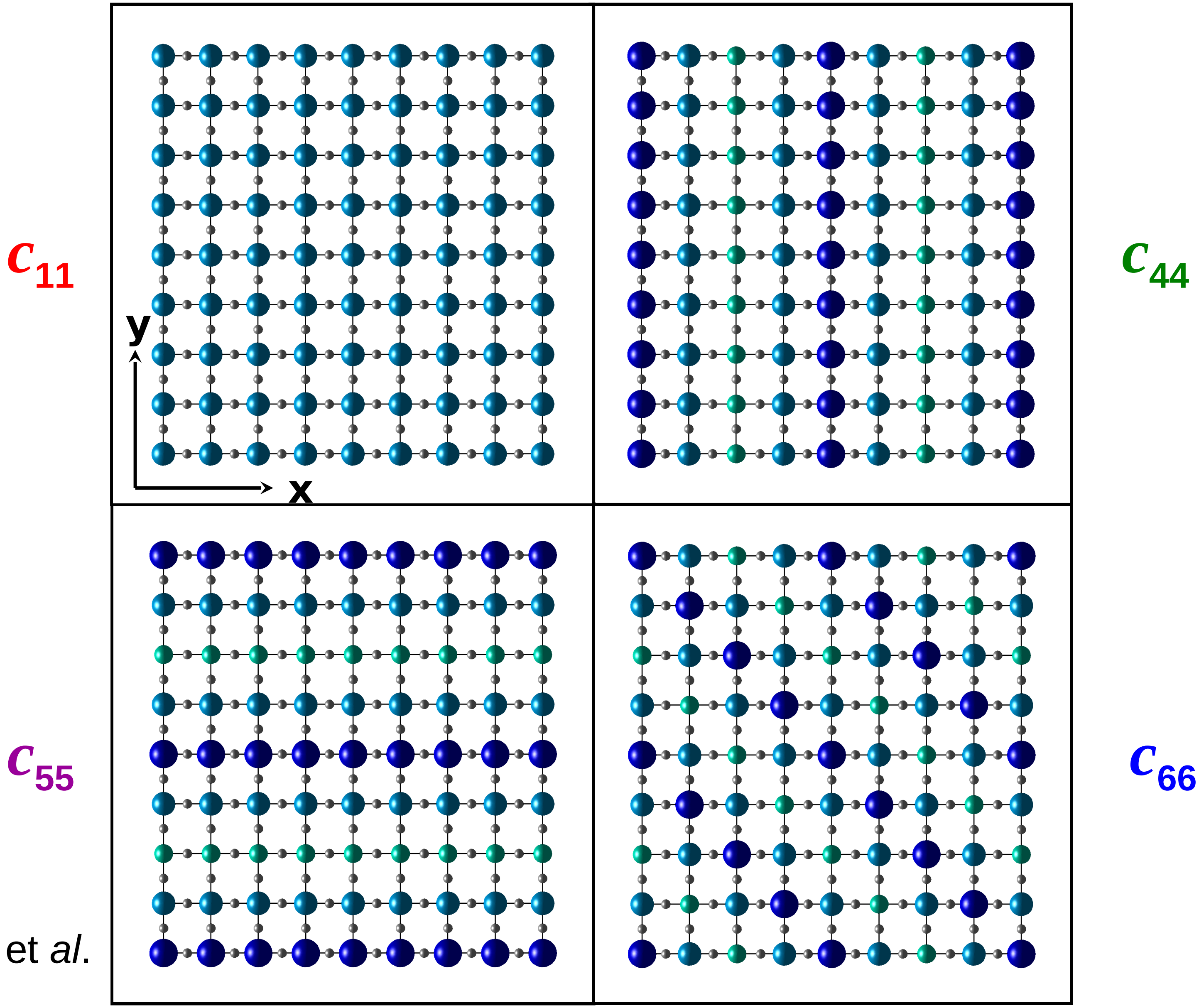
T_{co}



Phase diagram of the competition between SC and stripe order tuned by a magnetic field at T=0

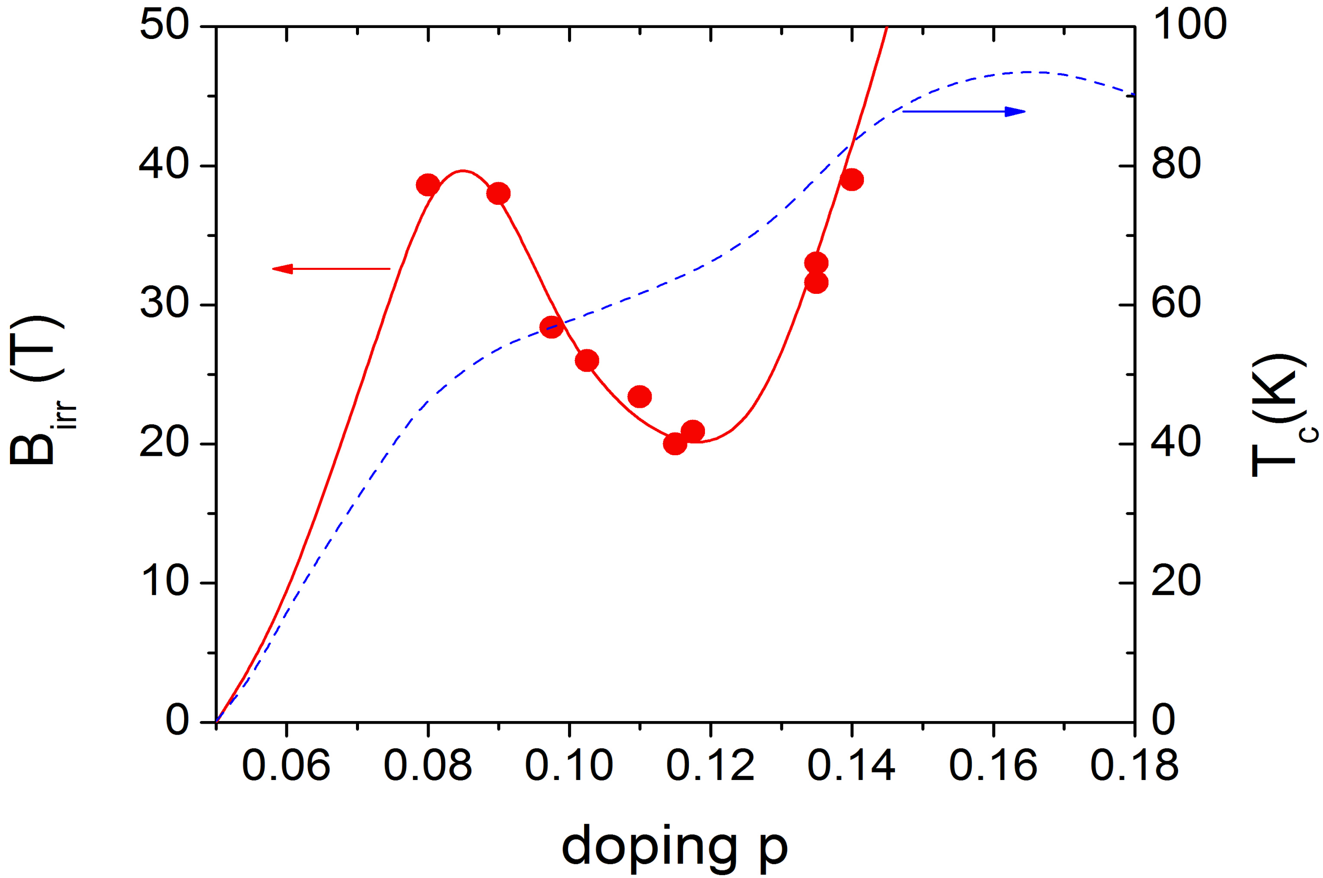


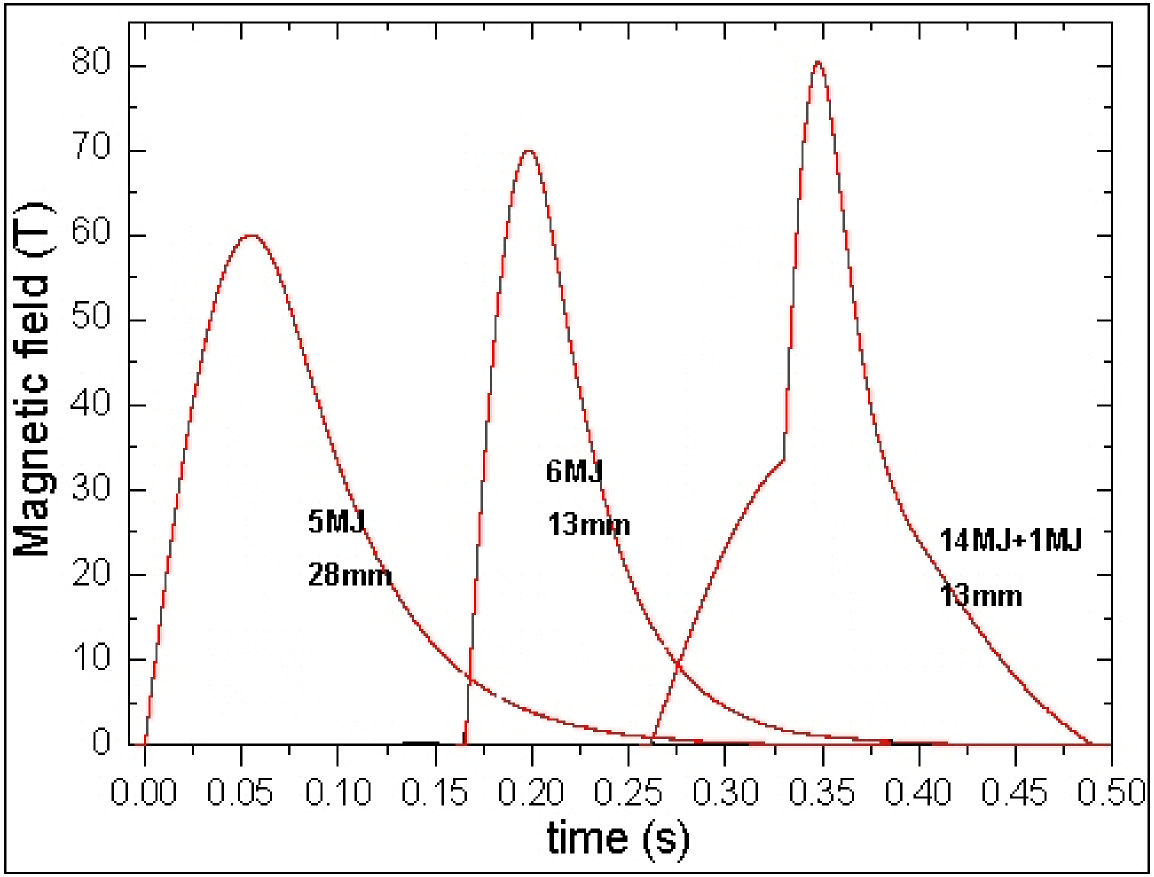
(Adapted from Demler et al, PRL'01)



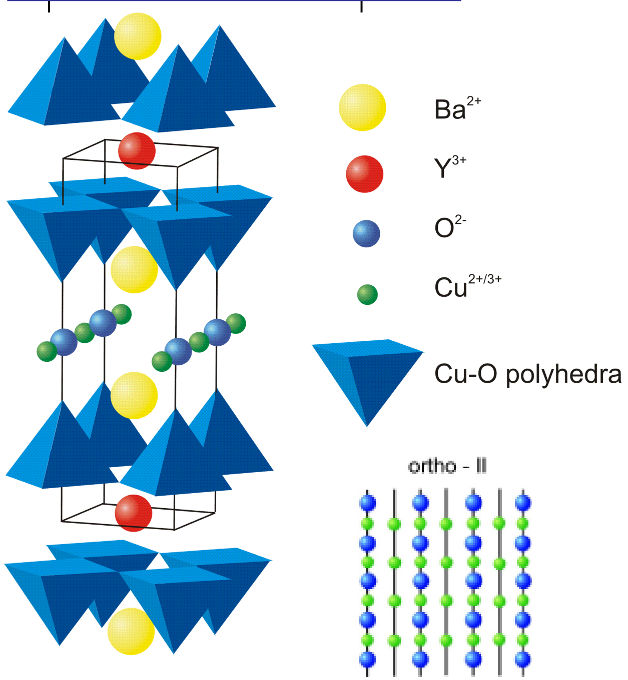
D. LeBoeuf et *al*.

Irreversibility field: $YBa_2Cu_3O_y$




80
70
60
50
40
30
20
10
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Magnetic field (T)
time (s)
5MJ
28mm
6MJ
13mm
14MJ+1MJ
13mm

$YBa_2Cu_3O_y$ (Y-123)



- y=6.51: T_c = 57.5 K
- *y=6.54:* T_c= 60 K

p ~ 0.1

The overdoped case: $Tl_2Ba_2CuO_{6+\delta}$

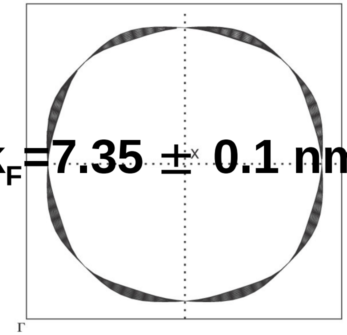
- F=18100 ± 50 T

Onsager relation : $$F = \frac{\varphi_0}{2\pi^2} A_k$$

$A_k = \pi k_F^2$ ⇒ k_F=7.42 ± 0.05 nm^{-1}

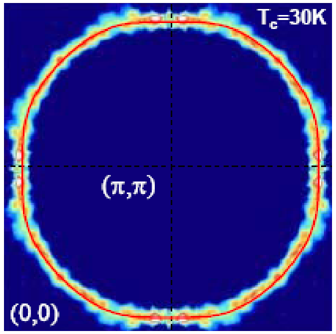
(65 % of the FBZ)

AMRO



Hussey *et al*, *Nature*'03

ARPES



Platé *et al*, PRB'05

Luttinger theorem : $$n = \frac{2A_k}{(2\pi)^2} = \frac{F}{\varphi_0}$$

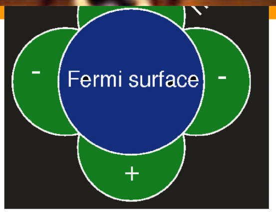
⇒ Carrier density: n=1.3 carrier /Cu atom (n=1+p with p=0.3)

Electronic specific heat: $$\gamma_{el} = \frac{\pi N_A k_B^2 a^2}{3\hbar^2} m^* \quad \Rightarrow \quad \gamma_{el} = 6 \pm 1\,\mathrm{mJ/mol.K^2}$$

For overdoped polycristalline Tl-2201: $\gamma_{el} = 7 \pm 2\,\mathrm{mJ/mol.K^2}$ (Loram et al, Physica C'94)

All the numbers are in excellent agreement with
- in-field probes: AMRO, Hall effect
- zero field probes: ARPES, thermodynamic …

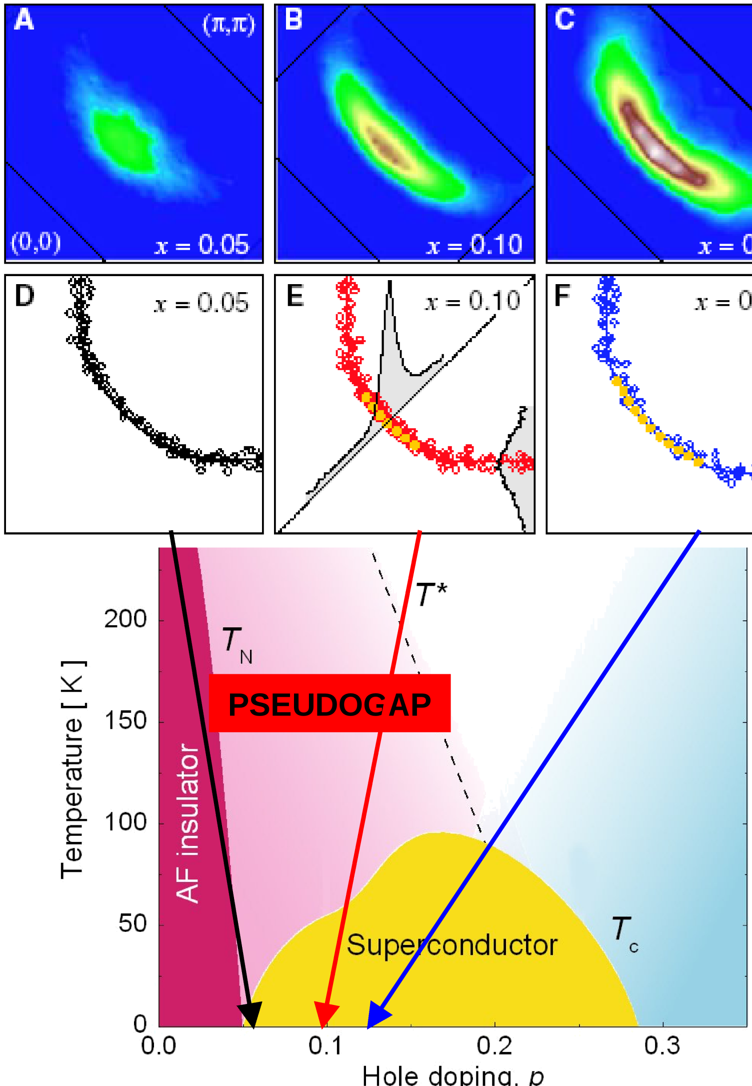
Pseudogap phase

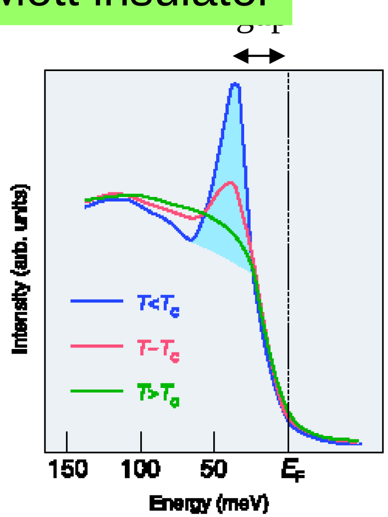


$Ca_{2-x}Na_xCuO_2Cl_2$

K. Shen *et al.*, Science'05

The case for the doped Mott insulator



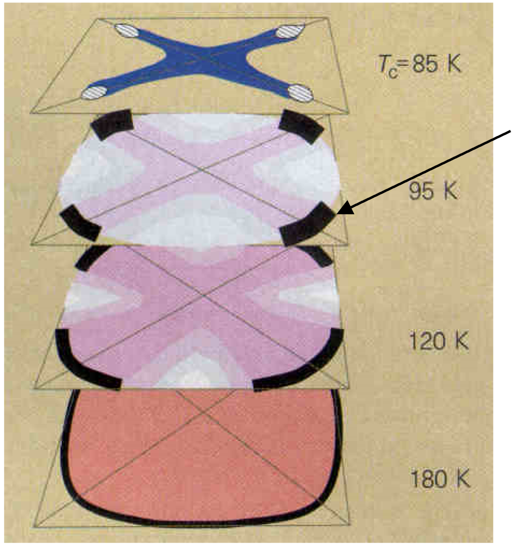


k ~ (O, π) → anti-nodal

I ∝ occupied state (k, ε)

$T<T_c$: quasiparticle pic

$T>T_c$: No QP but gap remains



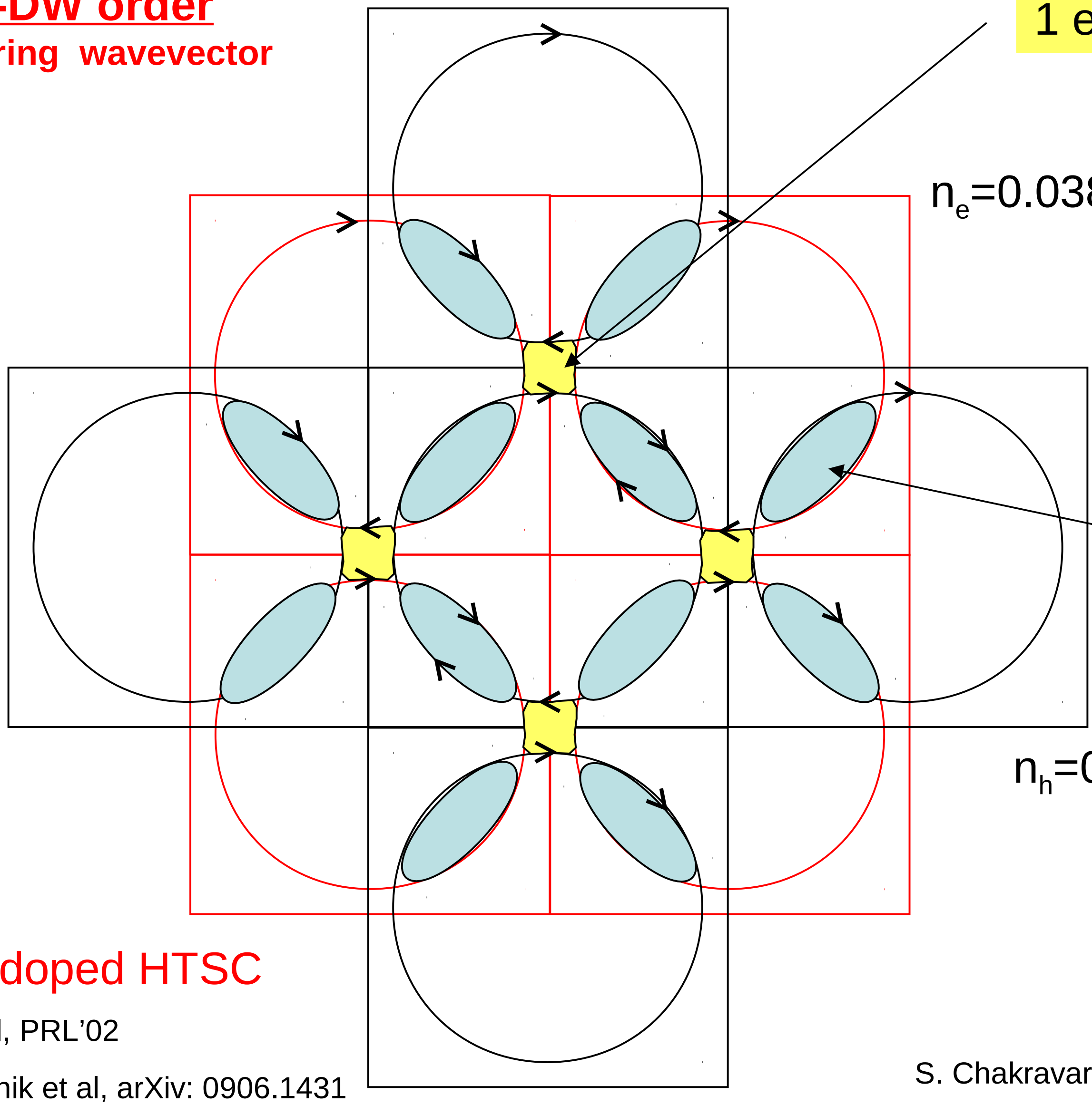
Fermi Arc

M. Norman *et al*, *Nature*'98

FS reconstruction scenario

AF / *d*-DW order

(π, π) ordering wavevector



1 electron pocket

F_{SdH}=530 T

n_e=0.038 electron/Cu atom

$\mu_e \gg \mu_h$ at low T

2 hole pockets

F_{SdH}=990 T

n_h=0.138 hole/Cu atom

$n=n_h-n_e=p=0.1$

e.g. electron doped HTSC

N.P. Armitage et al, PRL'02

T. Helm, M Kartsovnik et al, arXiv: 0906.1431

S. Chakravarty and H.Y. Kee, PNAS'08